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LOW-ENERGY PROTON ($0.5 \le E \le 50$ keV) OMNIDIRECTIONAL INTENSITY CONTOURS IN THE EARTH'S OUTER RADIATION ZONE AT THE MAGNETIC EQUATOR*

by

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Abstract

Observations of low-energy proton intensities within seven selected energy bandpasses spanning the energy range $0.5 \le E \le 50$ keV are summarized in L-value versus time diagrams for the period 10 June through 23 July 1966. These contours of omnidirectional, differential proton intensities were calculated via measurements of the directional, differential spectrums of the proton intensities with a sensitive electrostatic analyzer array borne on the earth-satellite OGO 3 at mid- and low latitudes in the outer radiation zone and are normalized to a geomagnetic latitude 0° (magnetic equator). These L-versus-time diagrams provide a compact, useful summary of these unique observations of proton intensities over L-values ranging from ~ 3.0 to 12 and promote further insight into the morphological features of one of the most dynamically important components of magnetospheric plasma.

I. Introduction

Comprehensive observations of the directional, differential energy spectrums of low-energy proton and electron intensities, separately, over large regions of the earth's radiation zones were first achieved with a sensitive electrostatic analyzer array borne on the earth-satellite OGO 3 launched in early summer 1966. Salient among these unique measurements of charged particles within the energy range 100 eV $\lesssim E \lesssim$ 50 keV were (1) first direct detection and survey of the proton distributions which form the extraterrestrial ring current [Frank, 1967a], (2) first simultaneous measurements of the spectrums of low-energy proton <u>and</u> electron intensities (300 eV $\lesssim E \lesssim$ 50 keV) near the magnetic equator in the vicinity of the earthward termination of the plasma sheet in the dark hemisphere of the magnetosphere [Frank, 1967b, c, d; Frank and Shope, 1967], (3) first determination of the energy spectrums of electron intensities over the above energy range during quiescent and storm-time magnetic conditions near the magnetic equator in the outer radiation zone [Frank, 1968], (4) an independent determination of the atomic hydrogen densities over the altitude range 1.5 to 4 R_E (R_E, earth radii) within the terrestrial exosphere [Swisher and Frank, 1968], and (5) first rigorous elimination of the possible, and previously reported, existence of extremely large fluxes of ions deep within the inner radiation zone [Frank and Swisher, 1968]. More recently, these electrostatic analyzer arrays have been used (1) to provide first evidences of the existence of significant intensities of solar protons ($5 \lesssim E \lesssim 50$ keV) in the interplanetary medium and to determine their energy spectrums and angular distributions [Frank, 1969a], (2) to show the existence of and to determine the character of two distinct low-energy proton distributions in the geomagnetic tail [Kanbach and Frank, 1969] and (3) to obtain first direct detection of the asymmetric injection of 'ring current' protons into the outer radiation zone during the onset of geomagnetic storms [Frank, 1969b].

In order to supplement the above detailed studies of these recent measurements of low-energy proton and electron intensities in the earth's magnetosphere, our present purpose is directed toward summarizing the unique series of observations of proton intensities within the outer radiation zone in a comprehensive graphic form to furnish a basis for additional insight into the character of this important component of magnetospheric plasma and a compact medium for comparison with further satellite and ground-based measurements.

II. Observations

The first curved-plate electrostatic analyzer array designed explicitly for comprehensive measurements of the nearly isotropic angular distributions and broad energy spectrums of proton and electron intensities within the energy range 100 eV $\lesssim$ E $\lesssim$ 50 keV which populate the earth's magnetosphere and its environs was launched with the third Orbiting Geophysical Observatory (OGO 3) in 1966. The design and calibration of this Low Energy Proton and Electron Differential Energy Analyzer (abbreviation, LEPEDEA) and the satellite orbit (launch, 7 June 1966; initial apogee 128,500 km and perigee 6700 km geocentric radial distances; inclination, 31°; period, 48.6 hours) have been previously discussed [Frank, 1965, 1967b, c; Frank, Stanley, Gabel, Enemark, Randall and Henderson, 1966; Frank, Henderson and Swisher, 1969]. However, as an aid to the reader it is convenient to note here several of the major features of the instrumentation. At launch the local time of the direction from the center of earth to spacecraft apogee position was ~ 22:00. A composite system of reaction wheels and gas jets provided a predetermined, monitored orientation of the various spacecraft-referenced coordinates with respect to the directions from the satellite to earth and the sun and with respect to the satellite orbital plane.

The University of Iowa instrumentation includes four cylindrical-plate electrostatic analyzers to select charged-particle energy per unit charge (E/Q) and continuous-channel electron multipliers as charged-particle detectors. Each of the two pairs of electrostatic analyzers provides simultaneous measurements of the directional intensities of protons and electrons, separately, within the same energy bandpasses over an energy range extending from approximately 100 to 50,000 eV. Thirteen, essentially contiguous bandpasses spanned this entire energy range for each particle species. Energy resolution and analyzer constants of this instrumentation were $\Delta E/E \simeq 0.5$ and ~ 7.5 eV(volt)$^{-1}$. The directions of the fields of view of these two electrostatic analyzers, designated LEPEDEA's 'A' and 'B', are orthogonal and are directed parallel to spacecraft body Cartesian axes, + Z (toward earth during normal spacecraft operations) and + Y, respectively. These fields of view are approximately rectangular with dimensions 6° x 22°. The spacecraft attitude control system functioned normally from launch until 23 July 1966 when the spacecraft was commanded into a spin-stabilized mode due to the failure of a power converter associated with the attitude control system. All observations presented herein were acquired during the period of proper functioning of this attitude control system.

Our goal for the present analysis is to construct contours of proton intensities as functions of the magnetic shell parameter L and time, similar to those which have previously been published for outer zone electron intensities with energies > 40 keV, > 230 keV and > 1.6 MeV observed with Explorer 14 [Owens and Frank, 1968]. An example of these contours of constant omnidirectional intensities of electrons at the magnetic equator is provided in Figure 1 which has been included here both as an example and for comparison with the low-energy proton contours for a period of similar magnetic activity (i.e., the occurrence of two periods with geomagnetic storms separated by an interval of relative magnetic quiescence). The construction of proton omnidirectional intensity profiles <u>at the magnetic equator</u> proceeded by approximating the observed proton directional intensities $j(\alpha_\circ)$ within a given energy bandpass at a specified L-value and equatorial pitch angle $\alpha_\circ$ with an assumed functional dependence upon $\alpha_\circ$,

$$j(\alpha_\circ) = j \sin^n \alpha_\circ$$

where j and n are functions of L. Since the angular distributions of proton intensities observed were not greatly anisotropic ($0.5 \lesssim n \lesssim 2.0$) over the relatively broad range of equatorial pitch angles, $20° \lesssim \alpha_\circ \lesssim 90°$, viewed with the electrostatic analyzers, the inaccuracies incurred with the above assumption are judged to be less than the uncertainties in the absolute values of directional intensities which are assessed at $\lesssim 30\%$. For a given L-value four measurements of intensities were used to determine the constants j and n. These observations were obtained as the satellite crossed the L-shell during consecutive inbound and outbound segments of the satellite trajectory (i.e., two measurements each, LEPEDEA's 'A' and 'B'). Typical differences in time (U.T.) and geocentric local time at L = 5.0, for example, were ~ 3 hours and ~ 7 hours, respectively. No large persistent disparity between the two-point angular distributions was evident within these sets of inbound-outbound orbit segments. The geocentric local times for measurements reported here ranged from ~ 16:00 to 01:00 (~ local evening-midnight quadrant). Since the 'dumping cone' of pitch angles at the magnetic equator is only several degrees or less in half angle for $L \gtrsim 4$, the omnidirectional intensities of protons at the equator were approximated by integration of the above expression for the directional intensities over the entire solid angle subtended by a unit sphere. Further, the B and L coordinates (and hence α_o) are computed by utilization of the Jensen and Cain [1962] coefficients for the geomagnetic field derived from measurements by <u>ground-based</u> magnetic observatories. This magnetic field model is invoked as a familiar <u>reference system</u> for the present observations in lieu of an eventual realistic field model which will self-consistently account for the distortions attributable to these proton populations [cf Frank, 1967a].

The omnidirectional intensities of protons within seven energy bandpasses, $0.5 \leq E \leq 50$ keV, over $L \simeq 3$ to 12 at the magnetic equator were extracted from all useable telemetry for the period 10 June through 23 July 1966. A representative sampling density of the directional intensities of protons ($16 \leq E \leq 25$ keV), for example, in a L-versus-time coordinate system is displayed in Figure 2. The gray, irregular zones appearing on this chart indicate major periods during which telemetry for this instrumentation was not acquired. Contours of constant omnidirectional intensities of protons within energy bandpasses $30 \leq E \leq 50$ keV, $16 \leq E \leq 25$ keV, $11 \leq E \leq 19$ keV, $7.0 \leq E \leq 12$ keV, $3.0 \leq E \leq 5.0$ keV, $1.1 \leq E \leq 1.8$ keV and $450 \leq E \leq 750$ eV as functions of magnetic shell parameter L and Universal Time are summarized in Figures 3 through 9. The units of these intensity contours are $(cm^2\text{-sec-eV})^{-1}$, average differential intensities within the above bandpasses of the electrostatic analyzers. Typical intensities of protons ($30 \leq E \leq 50$ keV) at $L \simeq 7$, for example, are 2 to 5×10^3 $(cm^2\text{-sec-eV})^{-1}$ (see Figure 3). Dotted areas of these charts indicate periods during which no reliable telemetry is available or regions in which the instrument responses approached background values and dashed lines identify contour interpolations. Daily sums of magnetic disturbance indices, ΣK_p, and three-hour averages of $D_{ST}(H)$ in units of gammas (γ, $1\gamma = 10^{-5}$ gauss) are included at the bottom of each graph as brief summaries of magnetic activity. Two moderate geomagnetic storms occurred during this period with peak main phase depressions $\sim -30\gamma$ and -50γ on 23 June and 9 July, respectively. For comparison with the electron omnidirectional contours of Figure 1, it is noted that moderate geomagnetic storms with main phase decreases of $\sim -70\gamma$, -30γ and -40γ occurred on 10 February, 8 and 10 March 1963, respectively.

III. Summary

The charts of omnidirectional proton intensities within the energy range $0.5 \leq E \leq 50$ keV as functions of magnetic shell parameter L and time (U.T.) at the magnetic equator in the outer radiation zone presented in Figures 3 through 9 are an effective method for summarizing the gross features of these proton distributions. Phenomena such as the apparently incessant presence of a partial 'ring current' of protons at $L \gtrsim 6$ during all magnetic conditions in the evening-midnight sector of the magnetosphere and the penetration of these protons to L-values deep within the outer radiation zone with the onset of geomagnetic storms are immediately evident in these L-versus-time contours of equatorial proton intensities. No large local-time dependence for proton intensities was evident during the analysis of these two months of observations within the local evening-midnight quadrant of the magnetosphere. However, further surveys over a broader range of local time do display a pronounced dependence of these proton spatial distributions upon local time and provide evidences that the 'quiescent ring current' proton intensities centered at $L \sim 6.5$ are most intense in the vicinity of the early afternoon-midnight sector of the magnetosphere [Frank, 1969b]. Two general limitations upon the usefulness of these intensity maps should be noted here. First, the time resolution for resolving temporal fluctuations in the shape of the intensity contours is limited by the satellite orbital period, $\sim$ 2 days. Secondly, non-adiabatic gains and losses of proton intensities are not easily separated from adiabatic acceleration and relocation of the low-energy proton distributions since a geomagnetic field model derived from measurements with ground-based magnetic observatories [Jensen and Cain, 1962] has been adopted here as a reference coordinate system in lieu of a tractable and self-consistent description of the real geomagnetic field. In any case, the present graphic summaries of these extensive, unique observations of proton intensities provide a compact, valuable communication concerning the morphology of this important constituent of magnetospheric plasma.

Acknowledgments

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Figure Captions

Figure 1. Contours of constant omnidirectional intensities of electrons ($E > 40$ keV, > 230 keV, and > 1.6 MeV) as functions of magnetic shell parameter L and time (U.T.) at the magnetic equator during February through March 1963 [after Owens and Frank, 1968].

Figure 2. Sampling density for observations of proton ($16 \leq E \leq 25$ keV) intensities in L-versus-time coordinates with the electrostatic analyzer array borne on OGO 3 during the period 10 June through 23 July 1966. Each point denotes an intensity measurement.

Figure 3. Contours of constant omnidirectional intensities of protons ($30 \leq E \leq 50$ keV) as functions of magnetic shell parameter L and time at the magnetic equator for the period 10 June through 23 July 1966. The contour intensity increments are 1, 3, 5 and 7×10^n. Units are omnidirectional differential flux, protons $(\text{cm}^2\text{-sec-eV})^{-1}$, averaged over the instrument energy bandpass.

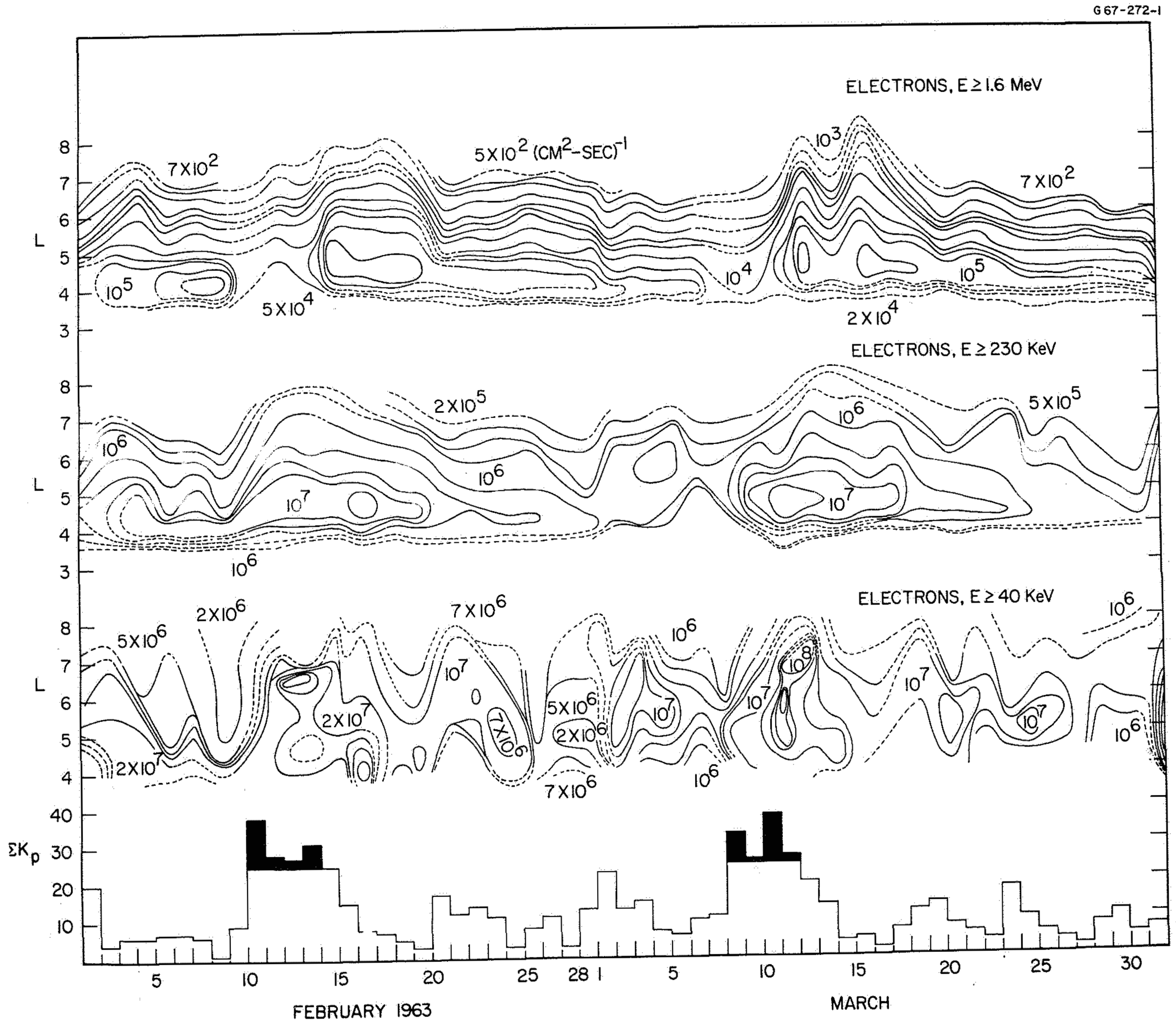

G 67-272-1
ELECTRONS, E ≥ 1.6 MeV
5 X 10^2 (CM^2-SEC)^-1
ELECTRONS, E ≥ 230 KeV
ELECTRONS, E ≥ 40 KeV
L
ΣKp
FEBRUARY 1963
MARCH

Figure 1

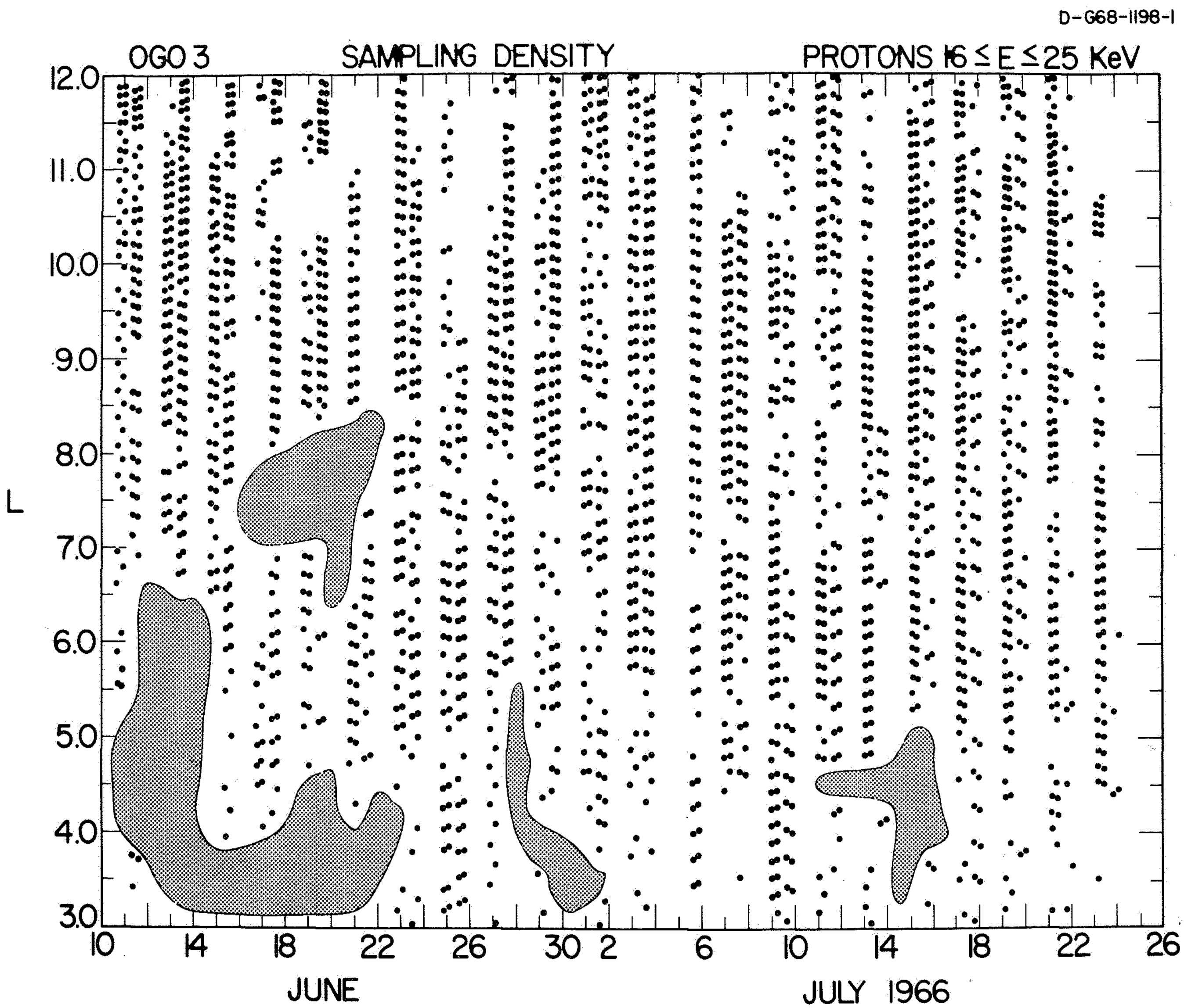

D-G68-1198-1
OGO 3
SAMPLING DENSITY
PROTONS 16 ≤ E ≤ 25 KeV
L
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
10
14
18
22
26
30
2
6
10
14
18
22
26
JUNE
JULY 1966

Figure 2

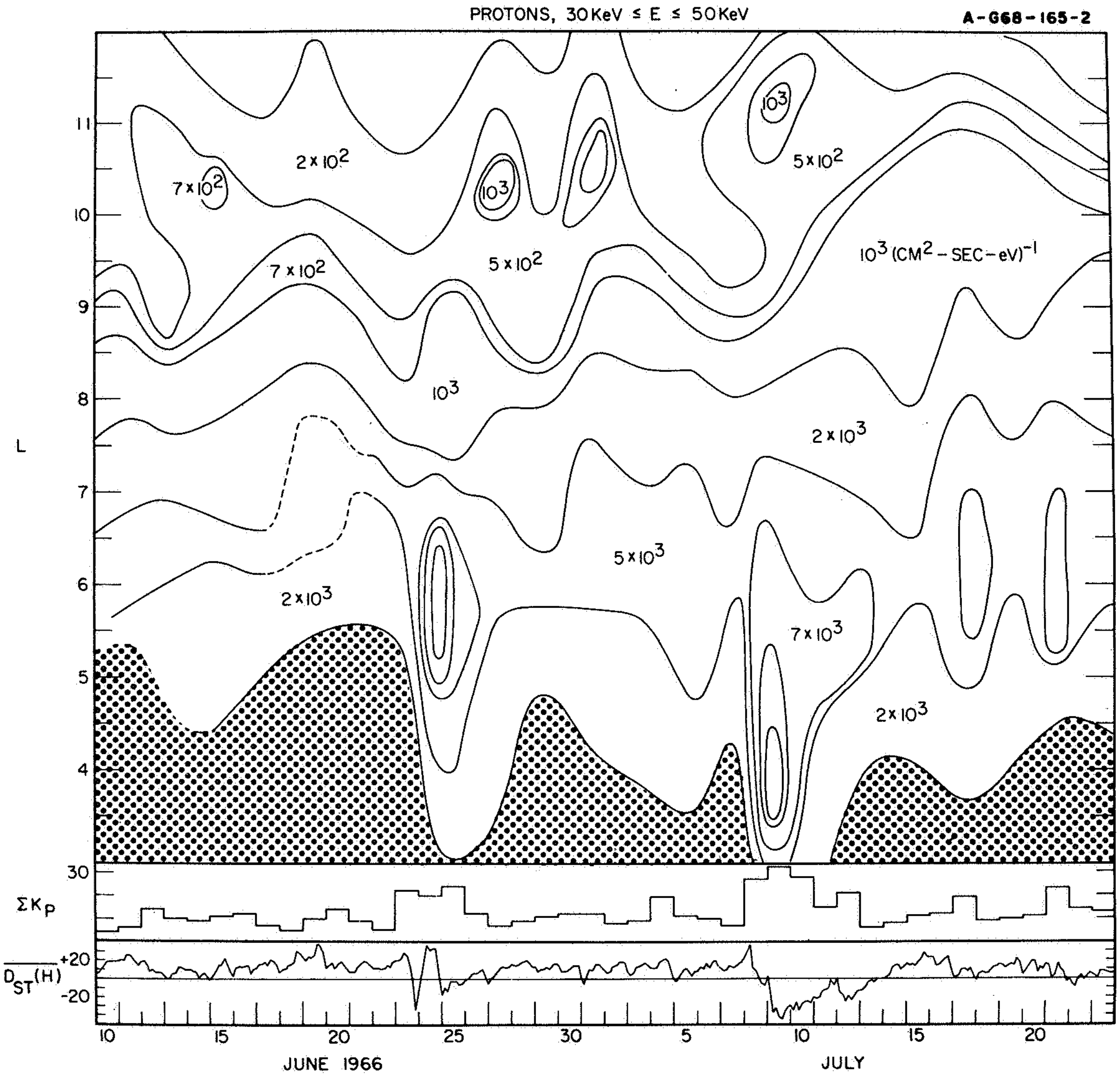
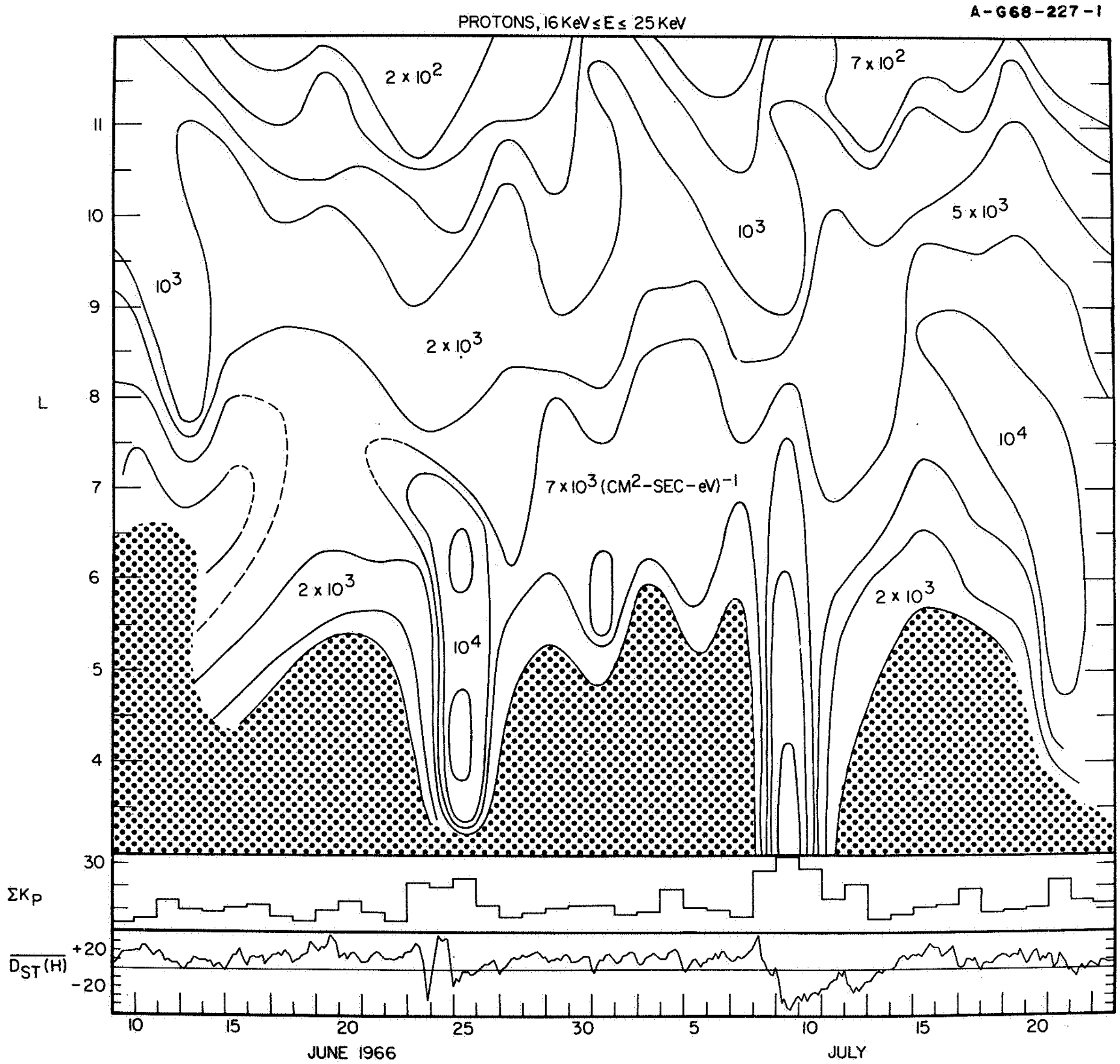
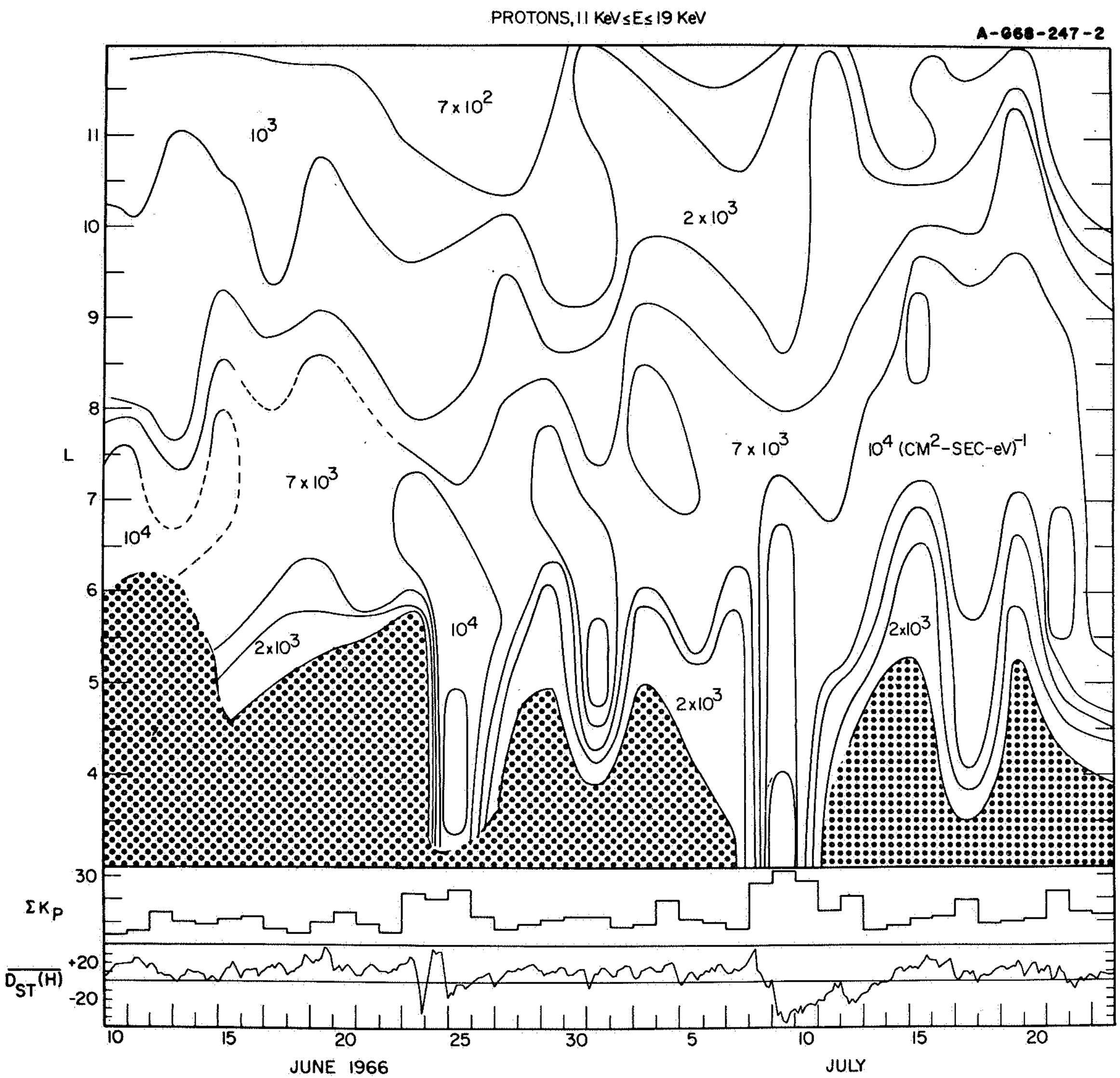

PROTONS, 30 KeV ≤ E ≤ 50 KeV
A-G68-165-2
L
11
10
9
8
7
6
5
4
7 x 10²
2 x 10²
10³
5 x 10²
7 x 10²
10³
5 x 10²
10³ (CM² - SEC - eV)⁻¹
10³
2 x 10³
5 x 10³
2 x 10³
7 x 10³
2 x 10³
30
ΣKp
+20
DST(H)
-20
10
15
20
25
30
5
10
15
20
JUNE 1966
JULY

Figure 3



PROTONS, 16 KeV ≤ E ≤ 25 KeV
A-G68-227-1
2 x 10^2
7 x 10^2
10^3
10^3
5 x 10^3
2 x 10^3
10^4
7 x 10^3 (CM^2-SEC-eV)^-1
2 x 10^3
10^4
2 x 10^3
L
11
10
9
8
7
6
5
4
30
ΣKp
+20
-20
DST (H)
10
15
20
25
30
5
10
15
20
JUNE 1966
JULY

Figure 4



PROTONS, 11 KeV≤E≤19 KeV
A-G68-247-2
L
11
10
9
8
7
6
5
4
10^3
7×10^2
2×10^3
7×10^3
10^4
10^4 $(CM^2\text{-SEC-eV})^{-1}$
2×10^3
30
ΣK_P
$\overline{D_{ST}(H)}$
+20
-20
10
15
20
25
30
5
10
15
20
JUNE 1966
JULY

Figure 5

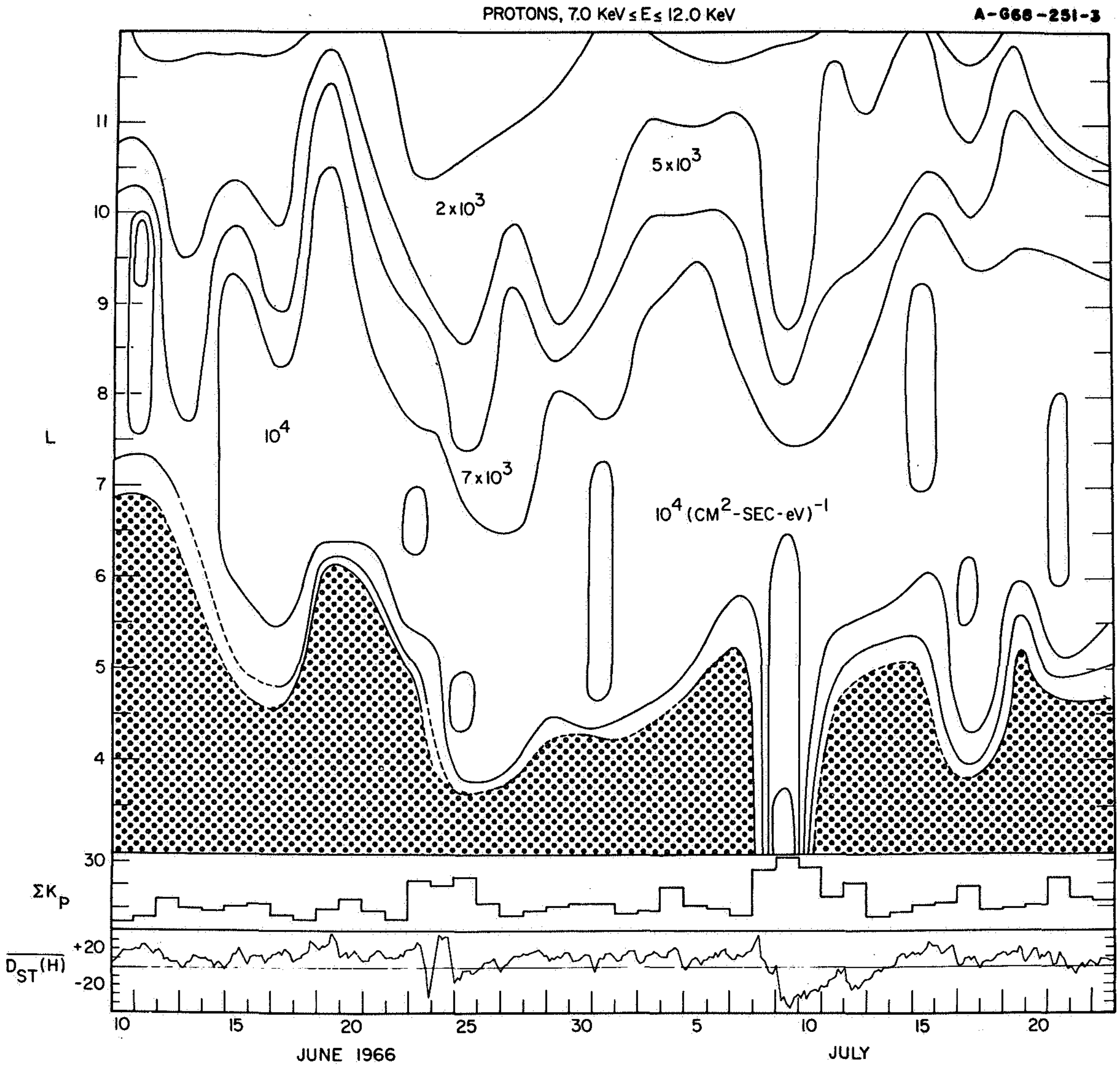

PROTONS, 7.0 KeV ≤ E ≤ 12.0 KeV
A-G68-251-3
L
11
10
9
8
7
6
5
4
2 x 10^3
5 x 10^3
10^4
7 x 10^3
10^4 (CM^2-SEC-eV)^-1
30
ΣK_P
+20
-20
D_ST(H)
10
15
20
25
30
5
10
15
20
JUNE 1966
JULY

Figure 6

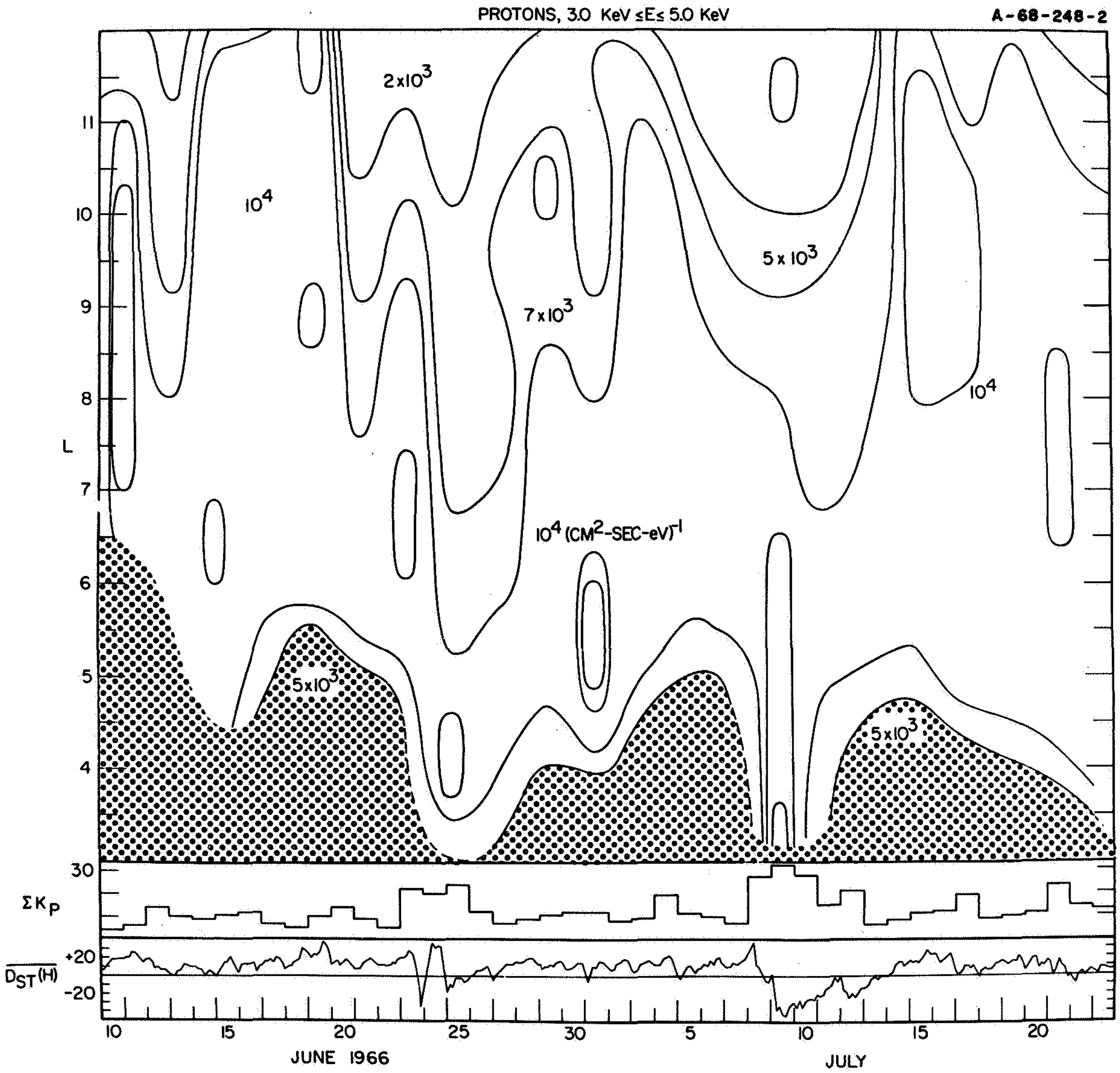

PROTONS, 3.0 KeV ≤E≤ 5.0 KeV
A-68-248-2
2x10^3
10^4
5x10^3
7x10^3
10^4
10^4 (CM^2-SEC-eV)^-1
5x10^3
5x10^3
L
11
10
9
8
7
6
5
4
30
ΣKp
+20
-20
DST(H)
10
15
20
25
30
5
10
15
20
JUNE 1966
JULY

Figure 7

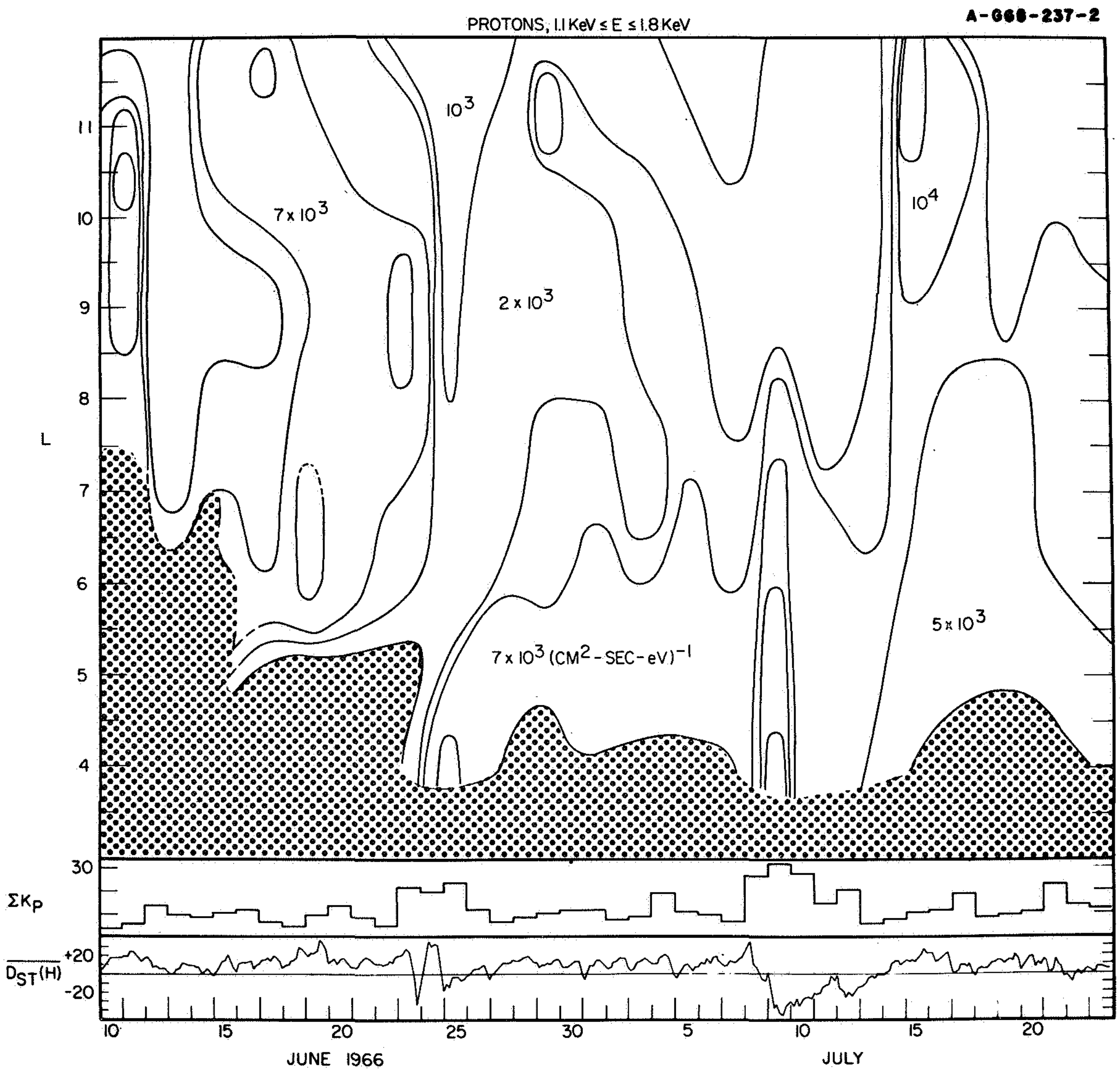

PROTONS, 1.1 KeV ≤ E ≤ 1.8 KeV
A-G68-237-2
L
10³
7 x 10³
2 x 10³
10⁴
5 x 10³
7 x 10³ (CM²-SEC-eV)⁻¹
ΣKp
30
+20
-20
DST(H)
JUNE 1966
JULY

Figure 8

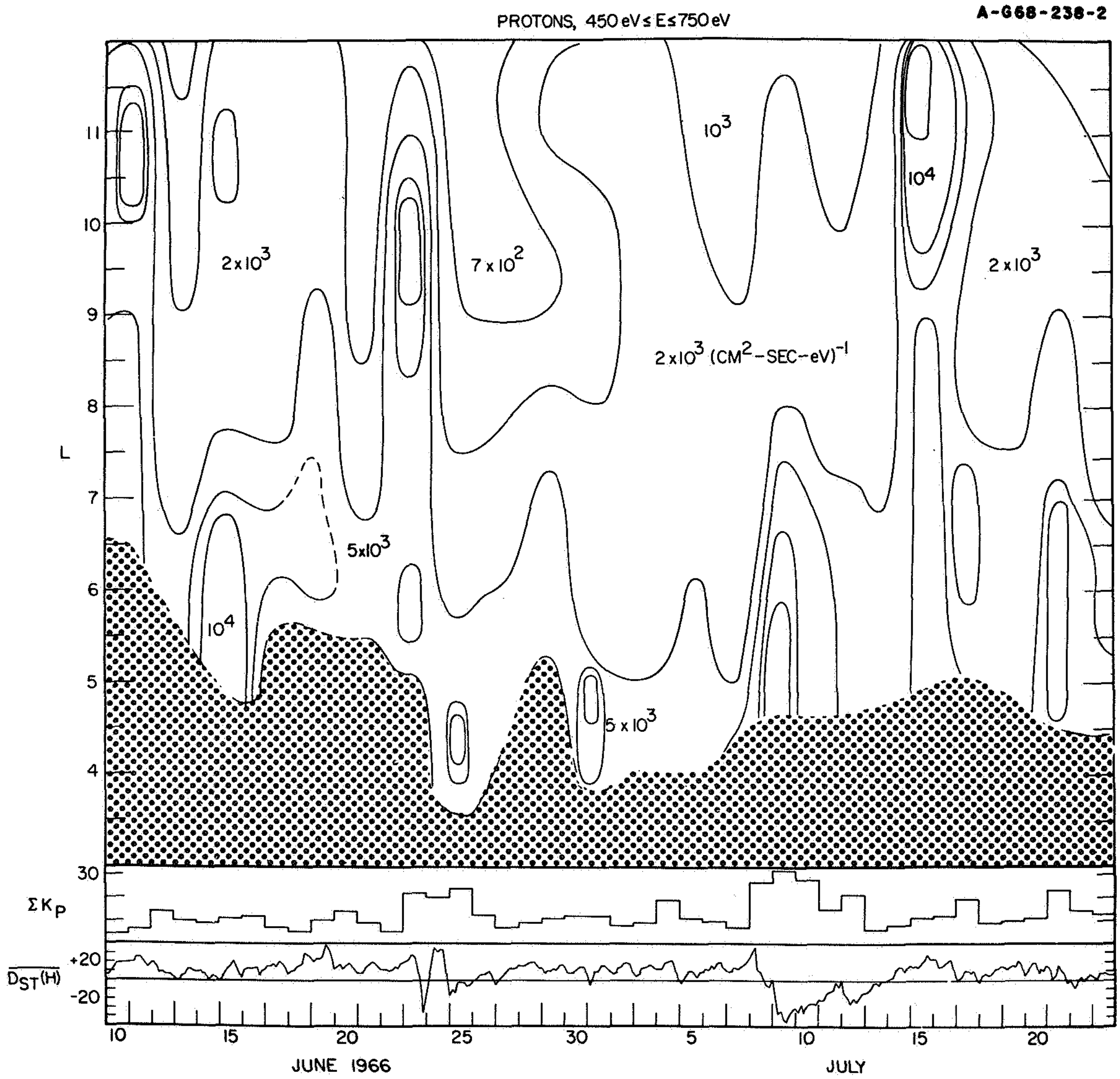

PROTONS, 450 eV ≤ E ≤ 750 eV
A-G68-238-2
L
11
10
9
8
7
6
5
4
2x10^3
7x10^2
10^3
10^4
2x10^3
2x10^3 (CM^2-SEC-eV)^-1
5x10^3
10^4
5x10^3
30
ΣKp
+20
DST(H)
-20
10
15
20
25
30
5
10
15
20
JUNE 1966
JULY

Figure 9

UNCLASSIFIED

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Extraterrestrial Ring Current						
Magnetic Storms						

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